DEPARTMENT OF SCIENTIFIC AND INDUSTRIAL RESEARCH.

BULLETIN No. 60.

Petroleum in New Zealand.

BY

J. HENDERSON,

Director, Geological Survey Branch, Department of Scientific and Industrial Research.

Issued under the authority of the Hon. D. G. SULLIVAN, Minister of Scientific and Industrial Research.

Extracted from the *New Zealand Journal of Science and Technology*, Vol. XIX, No. 7, pp. 401–26, 1937.

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PETROLEUM IN NEW ZEALAND.

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Introduction.

The increasing importance of petroleum to modern civilization needs no elaboration. Not only is it one of the major mineral products in the commercial world, but it is also of supreme importance in the existing state of technical science for measures of defence. The writer has been over most of the possibly petroliferous country of New Zealand, but valuable mineral deposits in general occupy so small a space, all the conditions essential for the economic accumulation of oil so rarely occur, and the chances of commercial success are so difficult to estimate that only the broader aspects of the occurrence of petroleum and its relation to sedimentation and earth structure are roughly outlined. This imperfect critical sketch of the Dominion's probable and possible oilfields is based, as far as possible, on observed verifiable facts and reasonable inferences from them; but the data are incomplete, their interpretation may require to be modified, or the explanation adopted for any group of facts may be only one of several.

The industry started on its modern phase some seventy or eighty years ago when the drilling for oil was carried out in Pennsylvania. At first well-location was largely a matter of chance, helped along by the presence of a seepage, by recourse to the divining-rod, or by the advice of the local expert. The geology of petroleum was not understood, and the conditions that aided or hindered its accumulation at any point were not comprehended. But seepage and drill gradually showed the way to the pools on or near the crests of the arches of the gently folded beds of the Appalachian fields, and I. C. White's anticlinal, or rather hydraulic, theory proved the value of careful observation of geologic structure and enormously enlarged the possibility of scientific help.

As production spread to other regions the geologist encountered other problems and developed broader theories of oil accumulation. Though the growth of applied science was slow, persistent attention to the problems involved has brought practical results that are more surprising than is ordinarily realized, though there is still a large element of luck in drilling an oil-well, and the proportion of payable wells is but a fraction of those put down. Petroleum differs from other mineral deposits in that there is no sharp distinction between prospecting and exploitation. The deposit cannot be followed down from its outcrop like other ore-bodies, and its position in depth has to be inferred from whatever data are accessible to the geologist, who painstakingly maps the surface geology, collaborates with the geophysicist to get other facts, and perhaps digs pits and puts down scout bores to get others. If the data are sufficient, the geologist can determine accurately enough the conditions of sedimentation and structure, but he cannot predict precisely how much oil there is, and there is no means, except by boring, of directly ascertaining this all-important information. The result is that the great producing companies carry out geological work on a very extensive scale and maintain staffs of experts of all kinds. Their geologists and geophysicists may be sent to any part of the world to explore new fields while their specialists in up-to-date laboratories work on samples sent to them and advise on rock porosity, oil sources, and other problems. But it must be confessed that our knowledge of the application of oil to industries and of the principles of sedimentation and earth structure is ahead of what we know of the history and origin of this product of the geological past. We know that oil is found in commercial amount in porous rocks; that it occurs rarely in coal-measures and other terrestrial beds but rather in strata laid down in shallow seas close to edges of basins of deposition; that it is carried along with the slow circulation of subsurface waters; and that it is trapped in earth structures of different kinds. Why it is present in one area or region and why it is absent in another apparently similar in all known essentials is an unsolved though fundamental problem of oil genesis.

That signs of petroleum are widespread is a commonplace, but it is not perhaps fully realized in how many countries oil is found though not obtainable in commercial amount. The United States of America has long been the most prolific producer, and it seems reasonable to assume that this oil is not a special endowment and that the sedimentary rocks of that country do not have unique characteristics but are similar to those of other regions. It is not, of course, suggested that the matter is simply one of proportion of area covered with strata that may contain oil. Other factors, such as technical skill and engineering plant—indeed, the stage of industrial development of the producing country—are of considerable importance. These factors, however, hardly apply to Canada and the great republic to the south, in which countries birth and infant growth of the oil industry were practically coincident; now the United States is the premier producing country, while Canada imports most of the oil she uses.

During the past seventy years many attempts have been made to find commercial oil in New Zealand, most success being achieved at New Plymouth, where a few wells yield a semi-commercial output. Other areas showing seepages and other indications of oil are known to be underlain by rocks that may well contain valuable oil deposits. In some areas suitable structures are apparent. Though the work hitherto undertaken did not

prosper, the results are inconclusive; much of it was ill-directed and futile, and of the remainder some holes did not reach their objectives owing to poor technical equipment or lack of funds. But enough is known to encourage the hope that commercial output is not improbable. Better understanding of the geological problems and improved technique in drilling and production engineering combined with adequate finance may well yield a rich harvest.

GEOLOGICAL FACTORS IMPORTANT IN OIL ACCUMULATION.

F. G. Clapp, the well-known oil geologist, in a series of papers has discussed the fundamental criteria for oil occurrence in commercial amount. The geologist in examining a region must endeavour to find answers for the following eight questions (1929, pp. 669–70) :—

"(1) Are the rocks of sedimentary origin?
"(2) Is the age of the strata (in part at least) similar to that of oilfield strata in some known oil or gas field?
"(3) Does a possible source of origin exist? If this be not apparent may it nevertheless be present?
"(4) Do porous beds or 'reservoirs' exist in which oil may be held in commercial quantity?
"(5) If so, does sufficient 'cover' exist above the reservoir beds to prevent the oil or gas from escaping to the surface and being lost?
"(6) Are the strata so slightly metamorphosed by heat or pressure that the oil has presumably not been driven out?
"(7) Does 'geological structure' exist suitable for concentrating oil in commercial quantity?
"(8) Are the hydrostatic conditions such as will not prohibit the accumulation of oil in pools?"

Clapp also writes (1927, pp. 685–86): "Although the writer will not go so far as to assert that drilling ought never to be undertaken in the absence of final affirmative answers to all the fundamental criteria, it seems safe to assert that test wells can be safely drilled if every question be answered favourably. If some criteria be answered favourably and the answers to others be unknown the venture may still constitute a 'good gamble' . . . if the strata be of an age in which oil or gas is elsewhere unknown, or if their character be such that no known source of origin can exist, or if no porous reservoirs appear to exist with an overlying impervious cover, or if local geologic 'structure' be nowhere suitable for concentrating oil in commercial quantity—if any of these defects exist, a field is probably not present."

Petroleum and inflammable gas are closely connected in Nature. Wherever there is oil there gas occurs; it is the expansive force of the gas in the oil that causes it to flow from wells. As the gas escapes this force weakens and flow decreases. On the other hand, oil does not always occur with gas; there are vast gasfields in America that have yielded no commercial oil, and the occurrence of inflammable gas in a swamp has no significance. Nevertheless, gas and oil are so intimately related in distribution and in chemical composition that both must be derived from the same substances and in the same general way. Modern industries dependent on the polymerization and hydrogenation of oils give point to this statement.

Early theories ascribed an inorganic origin to rock-oil which was thought to be formed by the action of water on metallic carbides or by the interaction of volcanic gases. Hydrogen, carburetted hydrogen, carbon monoxide, and carbon dioxide are common in all volcanic regions, and in suitable conditions of temperature and pressure oil may well be formed. The petroleum in the hot spring at Waiotapu may have been produced in this manner. The inorganic theories meet the requirements of the chemist, but supporting field evidence is lacking, and most geologists favour theories that derive the petroleum of commerce from organic substances—vegetable or animal, or both.

The usually accepted theory is that oil is the decomposition product of organic material entombed in sediments as these were deposited and there transformed into oil. The older view is that the natural earth processes of heat and pressure generate the petroleum by slow distillation. Others think that bacteria working in the putrefying organic debris in the absence of oxygen give rise to the oil at the time of, or very soon after, its deposition. Another view is that the oil is deposited as a sediment, being carried to the bottom with the clay particles, the oil being formed from the decay of plants on an adjacent landmass, or of diatoms growing in the sea, or from the decomposition of fish, foraminifera, and other animals.

Professor Edward Orton pointed out many years ago that petroleum was "abundantly and almost universally distributed among the unaltered sedimentary rocks of the earth's crust. The valuable accumulations of these substances are rare, it is true, but one can scarcely go amiss of petroleum, asphalt, or gas, at least in small quantities, among the stratified rocks that retain their original structure" (quoted by Dumble, 1915, p. 521). Some rocks, of course, contain far more oil than others, and these, though commercial deposits may not be found in them, are regarded as source rocks. Such are shales, mudstones, and all argillaceous sediments, especially if rich in plant and animal remains. The oil geologist, whether he believes that petroleum is derived from plant or animal remains or from both, likes to see thick extensive beds of shale black with vegetal matter and of mudstone and limestone rich in foraminifera. Sandstones, grits, and conglomerates, though they may be saturated with oil, are not regarded as source rocks; they serve as reservoir rocks in the pores of which oil squeezed out of other finer-grained rocks may accumulate.

Whether the process of initial formation was biochemical or geochemical, there can be no doubt of the importance of temperature and pressure prolonged through geological times. From the long-accepted idea of the slow metamorphism of coal with the elimination of volatiles the carbon-ratio theory developed. This explains why the proportion of fixed carbon of the ash-free coaly material in the strata of oilfields varies as the grade of the oil, and why when this proportion is more than 63 per cent. commercial deposits of such a volatile substance as petroleum are nowhere found.

The geologist, then, does not expect to find oil in commercial amount in the granites and schists of West Nelson and Fiordland, in the schists of Marlborough and Otago, in the Rotorua-Taupo thermal region, or in the Hauraki volcanic pile. The much-jointed, indurated, and cemented greywacke that forms most of the Southern Alps, the Kaikouras, the main axis of the North Island, and much other highland country in both Islands contains coaly material of too high a carbon ratio to be favourable for oil. On the other hand, the younger and less deformed greywackes and argillites of Jurassic and Triassic age from which the Hokonui and Kaihiku hills of

Otago are carved and which form the uplands west of the Waipa basin in South Auckland and of the Urewera country contain coaly matter with a carbon ratio ranging between 40 per cent. and 60 per cent. Here it must be made clear that the alteration the rocks have undergone may, from the point of oil occurrence, be more important than their actual age ; thus some of the schists and more altered greywackes of New Zealand are no older than the strata of the vast oilfields of Appalachia and Oklahoma. It must also be mentioned that volcanic debris and lava may but veneer rocks likely to contain oil.

" A reservoir in the geological sense is that portion of a sand-body or other rock in place, with pores of sufficient number and size as to be capable of holding and yielding a commercial quantity of oil or gas if they are present. It includes the whole porous volume whether it contains water, oil, or gas. An oil pool is that continuous portion of a reservoir containing oil. There may be several pools in one reservoir, separated by portions containing gas or containing water " (Johnson and Huntley, 1916, p. 57).

Reservoirs are of different kinds, the more usual being porous sandstones, jointed limestones, fissured rock, and limestones with cavities dissolved by water. Obviously, solid rock occupies a large part of any reservoir or pool. Sandstones (if loosely consolidated, referred to as sands) are much the commonest reservoir rock. Spherical grains of uniform size give the maximum pore-space. If grains of different size are present the smaller will occupy spaces between the larger and the rock will be tighter and less porous. Theoretically, equal-sized spherical grains give a pore-space of nearly half the mass, but even clean sands rarely have more than 28 per cent. of pore-space and the average may be about half this. Clay and calcareous and siliceous cements may clog the pores, which again may be so small that capillary forces and friction may check drainage and greatly reduce the effective porosity as compared with the theoretical. Indeed, the actual production from most pools in sandstone is but a fraction of the amount of oil in the sand.

" Cover " refers to the impervious or less-porous beds surrounding a reservoir, and especially those that overlie it. Such rocks are usually shales or mudstones, or at least contain a good deal of argillaceous material, but they may be oil-saturated, though finer-grained, sandstones which give up their oil less readily than the more open system of intercommunicating spaces that forms the reservoir. Though some sandstones are markedly persistent over wide areas, most show considerable differences in thickness and many lens out irregularly. Other sandstones are so extremely narrow and irregular that they are interpreted as beach bar or as fillings of current channels. Mudstones and shales are much more regular and persistent. Limestones in general are less porous than sandstones and the fracture and cavern types of reservoir are so irregular as to preclude the predicting of their capacity or even their presence.

As stated above, argillaceous beds rich in organic remains are regarded as the most possible source of petroleum. Such material when deposited contains large amounts of water, and when compacted by the weight of overlying sediments the reduction in pore-space is probably the most effective single cause in bringing about the concentration of petroleum. The water and oil move from the places of more compaction (that is, the muds) to those of less compaction (that is, to the sands). Other factors that assist migration and concentration are increase in temperature following deep

burial, cementation of pores, and circulation of underground water. The ultimate tendency of the compaction and consolidation of the strata is to force the water and oil to the surface. But irregularities in the deposition and cementation of the rocks and the folding and fracturing they suffer produce what are termed trap structures in which the moving water and oil are delayed and in which their separation takes place.

Differences in specific gravity bring about the separation of the oil from the water, the former rising to the higher part of the reservoir. Again, the surface tensions of the two liquids are different, and a fine-textured rock may allow water to pass through or actually absorb water that will altogether prevent the passage of petroleum. Thus oil-pools accumulate in reservoir rocks in trap structures. A common form of trap structure is where a reservoir bed lying between relatively impervious beds is arched up into what geologists term an " anticline." But there are other forms of trap structures created by folding of strata, by faulting, by cementation, by deposition or by the amount of water in the rocks, and an isolated lens of sandstone or a porous mass of any kind, no matter what its attitude or shape, if entirely contained in mudstone may become saturated with oil from the surrounding source rock.

In developed fields the production of some seems to be in proportion to the porosity and size of the reservoir at the wells, and in others faulting and sand-lensing are the principal factors ; but in the majority of fields structure is of great importance. In many of this majority structure in its strictest sense controls production, but in some the irregular reservoir conditions modify this relation and producing areas lie on the flanks of an anticline or migration along faults may cause erratic distribution. In general, structure conditions influence accumulation, and reservoir conditions, production.

Clapp (1929, p. 670), in discussing the importance of structure in relation to other essentials of oil accumulation in commercial amount, writes :—

" In considering the numerical order in which the structural criterion (see page 403 above) should be ranked, we may start with the axiom that structure is *one* of the criteria for the accumulation of oil. A matter of equal certainty is that undue weight must not be attached to the existence of suitable structure, for, in the absence of a satisfactory accord with the other fundamental criteria enumerated, oil in commercial quantities will not be found. The question we should all ask ourselves in general and as applied to every individual geological problem is *exactly what* relative importance to assign to structure ; for an anticline in a petroliferous province is not the sole desideratum. Each geologist must answer the question of the relative importance of structure in his own way. But he cannot avoid the conviction that structure is of great importance in oil accumulation, and that it must be adequately considered at some stage in the field studies."

In undeveloped territory that may contain oil the structure of the outcropping strata can generally be deciphered with considerable accuracy, whereas other essential facts often cannot be ascertained before boring is undertaken. In these circumstances structure becomes comparatively more important. Nevertheless, there are fields that would never have been found on structural evidence only. Most oilfields show definite relation to structure ; and in general geologists hold that good structures in unproved but possible country are worth boring unless other fundamental essentials for oil accumulation are positively unfavourable.

GENERAL STRUCTURE OF NEW ZEALAND.

New Zealand is the parts of the crests of great earthfolds or geanticlines in the south-west Pacific that rise above the sea. The principal ridge extends north-north-east through the South Island, the eastern part of the North Island, and thence below sea-level to the Kermadec and Tonga Archipelagos nearly to Samoa. Its submarine continuation south carries the Auckland, Macquarrie, and other island groups. The segment of the earth's crust occupied by the South Pacific Ocean, in sinking, is thought to have forced up this fold.

The North Pacific covers a still vaster segment, which, when it subsided, formed a series of folds that lie nearly at right angles to the New-Zealand – Tonga ridge, and the bathymetric map of the ocean north of New Zealand and east of Australia shows a number of shallow areas elongated in a general north-west direction. New Guinea and the Solomon Islands, the New Hebrides and New Caledonia, are high parts on different submerged ridges, and North Auckland peninsula is regarded as the crest of another similar fold. North Auckland is 1,500 miles or more from the edge of the sinking segment, and it rises above sea-level largely because it lies on the flank of the north-north-east fold. This latter strongly influences it. North Auckland strikes nearly north-west; Hauraki Range, which farther south lies on the east wing of the same fold, strikes at its north end north-north-west and opposite Tauranga nearly north; but the Patetere upland, its direct continuation, trends north-north-east opposite Rotorua, and sixty miles to the west the west limb of the North Auckland fold strikes east of north along the coast of the island.

The West Nelson highlands are interpreted as the root of a fold similar to that forming North Auckland. The elongated earth-blocks on the brittle crust of the fold give surface expression to the fold trends below. South from Golden Bay the central chain of the highlands has a sinuous course. First it strikes east of south, then south and south-south-west, next south, and finally south-west, where it lies against the main-elevation axis of the island. There are several subsidiary ranges which fault-angles and grabens separate from the main central chain. Subaqueous contours on the ocean-floor continue the ridge far to the north-west.

In the Province of Otago, at the south end of New Zealand, a broad anticline extending north-west across the widest part of the Island was probably raised by the same forces as raised North Auckland. The structure is in schist and is broken by numerous north-north-east-trending earth-blocks. A large highland mass stretching south-west from the northern part of the anticline continues the main mountain axis for a further 150 miles.

The higher portions of the ridges described above consist mostly of sedimentary rocks in part altered to schist, in part intruded by plutonic masses, and in general so intensely plicated, indurated, and sheared that commercial oil accumulation is hardly possible. These rocks are of Palæozoic and early Mesozoic age and, as well as suffering the Tertiary orogenic movements, were subjected to pressure and folding during the late Jurassic and earlier mountain-building epochs. The possible oil rocks of New Zealand are the little altered late Cretaceous and Tertiary strata that form a belt along the east side of the main north-east axis of elevation and, west of the axis, occupy the areas of New Zealand between the north-west-striking ridges and the angles they make with the main axes. In addition, parts of North

Auckland peninsula consist of relatively young rocks. Perhaps in all about 40 per cent. of New Zealand is covered with rocks that are not potential sources of mineral oil. The salient features of each region will be discussed later.

The history of earth-movements in New Zealand is imperfectly known, but is decidedly complex. The great movements known as revolutions that affected the whole world made their influence felt in New Zealand, as did other crust disturbances not so definitely correlated. The earliest crustal disturbance in New Zealand of interest to oil geologists occurred in Mesozoic times and is known as the Hokonui orogeny. By this mountain-building the rocks forming the Southern Alps, the Kaikouras, and the main axis of the North Island were intensely plicated along north-east lines, and those forming the uplands of north and west Auckland and the Kaihiku ranges of Southland less strongly, in a general north-west direction.

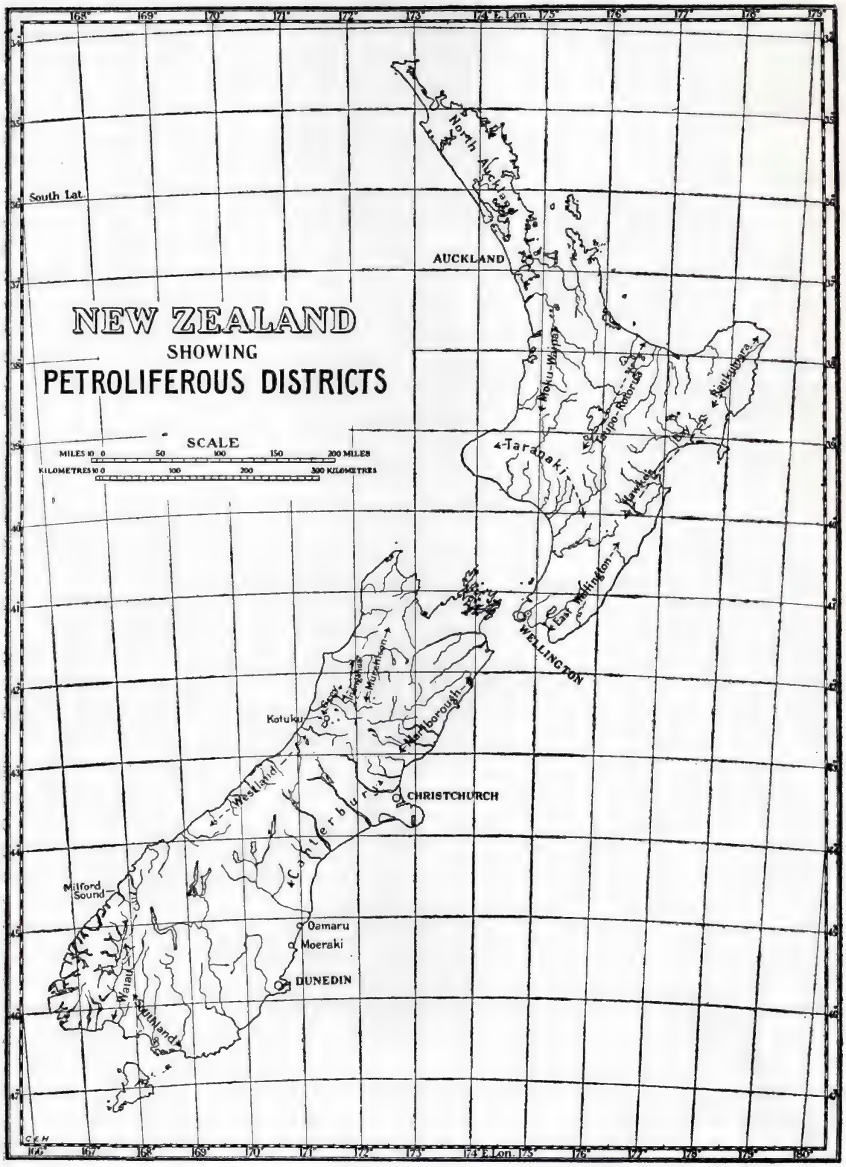
During the middle Cretaceous land seems to have occupied most of the New Zealand area. Erosion had reduced the country to a surface of low relief, or even to a peneplain, before earth stresses again broke and warped the crust. Thick gravels similar to those of the Canterbury Plains, probably the outwash from strongly uplifted earth-blocks, accumulated on low areas. Remnants survive in the Hawke's Crag breccia and Paparoa beds of the West Coast and in the Horse Range, Kyeburn, Henley, and Kaitangata conglomerates of Otago. Subsidence seems to have been fairly general, and the coarse gravels were followed by finer, and these by sands, and, finally, by mudstones with much lime. The sea during this, the world-wide Senonian transgression, advanced on other parts of New Zealand, depositing fine gravels and sands, followed by mudstone and argillaceous limestone, as the reduced area could furnish only weathered clay in small amount and rich in plant remains. The dark, carbonaceous mudstones and shales of these late Cretaceous and early Tertiary times are the likely source rocks of the petroleum seepages of many parts of New Zealand, notably of the Gisborne district and elsewhere along the east coast.

The crust became unstable about the end of the Eocene. Accumulated stresses crushed and crumpled the lately deposited strata, especially where thick. In some districts the resistant under-rocks were involved in broad warpings and the younger incompetent deposits on them escaped intense plication, though they show the effects of strong pressure. In some parts block-movements occurred, and in the East Cape district the old rocks were thrust over the young along a wide front for many miles.

During the rest of the Tertiary period earth-movements in the Gisborne - East Cape region seem to have been greater than in other parts of New Zealand. Here the Tertiary deposits are much thicker than contemporaneous beds elsewhere ; they are predominantly argillaceous and arenaceous, and of shallow water origin from top to bottom, so that the sea-floor must have sunk as fast as they accumulated. South of Hawke's Bay, and on the west side of the main axis, the sequence is thinner and less complete, some beds are missing, and limestones are decidedly more abundant. The theory is that the land close to the area of deposition rose as the infilled basin sank—that is, a crust fold was actively growing, the New Zealand ridge rising while the adjacent trough or geosyncline sank.

During the Oligocene the sea advanced over the land. There accumulated shallow water beds that differ much from place to place even in the same districts ; volcanoes were active in parts of the South Island, and in

several districts coal-seams occur. Widespread silty argillaceous sandstones followed, and in parts they were covered with massive limestone. There were one or two minor oscillations, the land being raised and again



depressed without much crustal distortion. Erosion had worn the surface to a low relief, subsidence had greatly reduced the land area, and, except in the Gisborne - Hawke's Bay region, little debris reached the sea.

Strong elevation occurred in the South Island sometime during the Miocene, since when this region, except for its northern end, has remained above the sea. In the North Island volcanoes became active and much fragmental material was thrown out, but deposition seems to have been otherwise hardly interrupted in the principal basins of deposition, the accumulation on the east side of the main axis being several times as thick as that on the west. The strata are predominantly silty argillaceous sandstones and, especially on the east side of the Island, contain much tuffaceous material.

Though apparently not greatly disturbed, the New Zealand area emerged about the close of the Miocene. In the depression that followed, the sea advanced widely over the eastern side of the North Island and over most of Taranaki and western Wellington. The earth-movements that gave New Zealand its present form belong to the middle and late Pliocene. The wedging-up along faults of the elongated strips of crust that form our present mountain ranges relieved most of the pressure, and the younger strata on lower areas were but little folded and broken. Since then the land has oscillated, but has suffered no major deformation; volcanoes have spread debris over large areas, rivers and glaciers have covered the lowlands with gravels and moraine, and the sea has worn away large tracts of soft strata.

RAUKUMARA DISTRICT.

Structure.

The Raukumara district, which forms the eastern part of the North Island from Gisborne northward, has a decidedly complex structure. The mountain divide consists of closely folded, steeply dipping greywacke and argillite of Mesozoic age, and has a general north-north-east course. In the Huiarau Mountains in the southern part of the district the rocks strike parallel with the general trend of the mountain axis, but in the Raukumara Ranges, which form the chief highland section in this region, the beds in most parts examined strike north-west, west-north-west, or east-west.

The lower country east of the highlands consists of marine sediments that are less indurated and much weaker than those of the mountains. These rocks range in age from the late Cretaceous to the Pliocene. At the north end of the district basic lavas and breccias, extruded during the early Tertiary, cover large areas. Earth stresses at about the same time forced hard Mesozoic pebbly greywacke over the late Cretaceous and early Tertiary strata. This overthrust has been traced along the Waiapu and Mata valleys and into the basin of the Koranga, a headwater branch of the Waioeka, which discharges to the Bay of Plenty. The shear-plane is flat or gently undulating. The overthrust sheet is presumed to have moved from north-west to south-east over a front of sixty miles, the movement in places being as much as twenty-five miles (Ongley, 1930).

The complexity of north-east and north-west to east-west trends is general throughout the region. At the north end a trough, two to three miles wide, let down between sub-parallel east-west faults, extends west from Hicks' Bay. This is the Wharekahika Graben. Five miles south of East Cape an important west-north-west fault reaches the coast; this fracture depresses all the country to the north many hundreds of feet. Twenty miles south from the Wharekahika Graben a wide syncline extends west for many miles into the highlands along the valley of the Tapuwaeroa,

a large branch of the Waiapu. North and south are anticlinal structures that reach the coast respectively near Port Awanui and at Waipiro Bay. The weak soft rocks of these anticlines and the syncline between them are so crumpled and intensely disturbed that these large structures become apparent only after regional mapping. Southward among the highlands and their foothills, in the upper Waipaoa basin, strong folds and well-marked faults, both trending north-west, disturb the Cretaceous and early Tertiary rocks, and there is some evidence of a broad syncline that extends from the headwaters of the Waipaoa north-west into the Motu basin. This belt of folding and faulting is twenty miles wide ; eastward is a belt, twelve miles wide, of middle and late Tertiary strata with dominant north-east trends, but still farther east the ten-mile coastal strip shows prominent west-north-west and east-west crush zones which reach the sea at Whangara, Kaiti, and other points and may continue the north-west folds of the Upper Waipaoa. A strong east-west fault-zone, termed the Waerenga-o-Kuri Fault, separates the Raukumara section of the East Coast region from the adjoining section. Between this fault-zone and southernmost structure line (Totangi Fault) of the Waipaoa group of north-west folds the strata dip gently and uniformly south, forming an extensive homocline near the south edge of which a wide syncline occurs in the basin of the Hangaroa branch of Wairoa River.

An open regular syncline, eight to ten miles across, extends along the foot of the highlands from the upper Waipaoa north-east for sixteen miles. To the south, and offsetting this structure, a still larger synclinal, also formed of middle and late Tertiary beds, stretches from Totangi Fault north-east for thirty miles towards Tokomaru Bay. This synclinal is about twelve miles wide, is asymmetrical—the trough lying well to the south-east—and is much faulted and warped. A fault-belt stretches along its south-east margin, and another, still more prominent, traverses the centre of the area for most of its length and brings small areas of early Tertiary rocks to the surface. Well-marked faults near the coast in the vicinity of Gable End Foreland have north-east strikes. The ten-mile coastal strip west of this fault-zone has a most complicated pattern of faults and warps. The beds exposed range in age throughout the Tertiary, the older strata appearing at the surface at many structurally high points.

Oil Possibilities.

Indications of the presence of oil are widespread in the Raukumara district—petroleum seepages, gas emanations, mud volcanoes, oil-smelling rocks, &c. These do not occur in the oldest rocks of the area, the indurated and much-jointed greywackes and argillites of the highlands, but in the weak late Cretaceous and Tertiary strata of the lower country. They are most abundant in or close to areas of the older groups of these beds where likely-looking source rocks, dark shales and carbonaceous mudstones, are thick and abundant. There are also porous sandstones, greensands, and fissile limestones in this part of the sequence that would form suitable reservoir beds. Some outcrops of sandstones are known to contain oil ; indeed, in the Waiapu district most late Cretaceous sandstones over hundreds of square miles smell of oil when freshly broken. The many thousands of feet of middle and late Tertiary mudstones and argillaceous silty sandstones would be excellent cover for any oil-pool and they themselves are possible source rocks.

Areas in the extreme north and extreme south of the district have relatively simple structure, but in the intervening three-quarters the structure is disordered, the complexity in a general way increasing from south to north. From Waipiro Bay north a large area of late Cretaceous and early Tertiary rocks lies between the coast and the highlands. The major structures seem simple enough, but minor complications are extreme, and, notwithstanding the numerous indications of oil, the finding of a commercial pool will be difficult and will involve much preliminary work. In this part of the district there is no late Tertiary cover. Along the foothills to the south-west similar conditions prevail and the major structures are less simple.

The 1,000 square miles of hilly country east of the foothills of the highlands and the coast between Waipiro Bay and Gisborne seems the most likely petroliferous area in the district. Tertiary rocks, chiefly belonging to the younger part of the sequence, are exposed, and in the southern part, where the youngest rocks are present, must be fully 15,000 ft. thick. In a general way the thickness decreases northward and the complexity of structure increases. There were a number of crust movements in the Tertiary, and as the structure developed the older strata were progressively more and more deformed. As already stated, the area is crossed by north-east and west-north-west structural trends, the former being prominent in the western half and the latter in the eastern. Faults and warps rather than folds dominate the structure, which, were it not that the younger beds contain a great deal of argillaceous matter, would be more favourable for the escape of petroleum than for its accumulation.

The strata of the larger unbroken areas form gentle, rather irregular synclinals. In many places the much narrower shattered zones between show outcrops of older Tertiary, so that they are probably acute sheared anticlines. Fault contacts of rocks of different ages prove substantial movement in some of them. Others contain bands of pug many chains across, and saline springs, gas emanations, and mud volcanoes occur. Several violent mud eruptions blown out by gas have taken place in historic times (Strong, 1931), and in 1929, a fortnight after the earthquake that destroyed Napier, an area of about 2 acres on one of the pug zones rose about 7 ft., the plastic crushed rock presumably being squeezed up along the fracture zone (Strong, 1933). This mud and that of the volcanoes contains angular and slickensided fragments of rock from the old Tertiary and late Cretaceous ; but no black shale has been noted.

The numerous escapes of oil and combustible gas in the Waipiro-Gisborne-Waitangi area will always excite interest. Features of geological history sequence and structure are both favourable and unfavourable, and any boring should be preceded by extensive field-work and a careful analysis of all the data available.

Most of the points mentioned in the above account of the Raukumara district are discussed in more detail by Henderson and Ongley(1920), Ongley and Macpherson(1928), Ongley (1924), and Clapp (1926).

HAWKE'S BAY - EAST WELLINGTON.

Structure.

The eastern half of the North Island is the crest of a great earth-fold or geanticline which is decidedly asymmetrical. The highest part of the fold, the mountain axis of the country, lies along the west and rises abruptly

from lowlands of unfolded strata that extend practically unbroken to Taranaki. On the east side the mountain face is quite as abrupt, but the low country is arranged in a series of furrows and ridges parallel with the range. Immediately east of the highlands a depressed strip extends along the whole axis, and east of this to the coast uplands occur. This general regularity of structure combined with the straightness of the whole great arch and the height uniformity of its crest suggests that the deforming stresses were fairly evenly applied. But different sections show decided differences in the thicknesses of the several formations involved and considerable differences in the details of the folds.

The simplest area is that about Hawke's Bay. There the depression east of the range consists of a great trough, the Wairoa Syncline. North of Hawke's Bay thick beds of young Tertiary slope gently east from the highlands to the trunk stream of the Wairoa basin, beyond which the same beds rise with dips equally gentle to the crest of a broad arch fifteen miles long and covering 100 square miles, the Mangapahi Anticline. Along the north shore of Hawke's Bay the Wairoa Syncline is forty miles across, but narrows northward, in which direction its trough gently rises. Several small folds arranged *en échelon* lie obliquely near its centre. The east wing of the Wairoa Syncline rises into a group of corrugations that have a general north-north-east strike. Nuhaka River flows along the trough of a syncline having a broad well-marked anticline on either side, their crests about six miles apart, but diverging northward. A fault on the flank of the eastern or Morere Anticline brings Cretaceous strata to the surface.

Southward the west wing of the Wairoa Syncline extends along the west side of Hawke Bay. All the strata for twenty miles back from the coast dip gently east and to the west overlap on the old rocks, the mountain-building faults traversing greywacke still farther west. The east wing of the syncline in this part is probably down-warped beneath the sea.

South of Hawke Bay the great syncline is as broad and well-marked as to the north, but the gravels of the Heretaunga Plain and the Ngaruroro flats cover over a hundred square miles along or near the trough. The Napier–Taihape Road crosses the mountain axis by the pronounced sag separating the Ruahines from the ranges to the north, and here remnants of the late Tertiary sheet of sediments extend nearly across the highlands. A narrow broken anticline of young Tertiary beds with a core of greywacke occurs at the eastern edge of the mountains. Southward the Wakarara Range forms a similar but much larger and greatly denuded anticline. The east wing of the Wairoa Syncline extends to the strong fault along the lower Tukituki valley, where Cretaceous and old Tertiary rocks appear from under the cover of younger beds. There are several warps and puckers on the higher part of this wing of the syncline. Flat-lying young Tertiary strata extend from the Tukituki to the coast where older rocks appear along a fault-zone.

A similar general structure persists southward in Hawke's Bay and East Wellington, though the folds are sharper and broken and the dislocations more pronounced. The Wairoa Syncline extends as the principal lowland of the region for one hundred miles to Eketahuna. Several faults striking south-south-west traverse the eastern limb of the syncline south of Hawke Bay. Near Takapau, forty miles south, the most westerly fault brings Mesozoic greywacke to the surface, and farther south the Waewaepa Range, also of greywacke, is uplifted along the same fracture. This continues south

to Masterton, whence southward it lies along the west base of the Tararua Mountains to Palliser Bay. From Takapau to past Eketahuna the Wairoa Syncline for sixty miles is about fourteen miles wide. At Eketahuna a north-south zone of faulting crosses obliquely, raising the country on the west side high enough to form highlands that extend south as the Rimutaka Range, in this part the eastern ridge of the Tararua Mountains. This block, which directly continues the Wairoa block southwards, is tilted west toward the main mass of the Tararua highlands, the Hutt Valley being a complex fault angle depression along part of its western edge.

The high, somewhat warped, eastern part of the Wairoa Syncline south of Hawke Bay grades southward into a hilly belt, six to eight miles wide, that extends south for a hundred miles. Different parts are known as the Raukawa, Whangai, and Puketoi ranges. These consist of tilted and warped blocks, elongated and folded along north-north-east lines, and formed chiefly of late Cretaceous and early Tertiary strata, in places veneered with late Tertiary beds.

East of this much-broken hilly belt is a strip of little-disturbed and, for the most part low-lying, country which extends from Hawke Bay to Tinui, a township twenty-four miles east-south-east from Eketahuna. It is about eight miles wide and a hundred miles long. The rocks are generally of middle Tertiary age and flat-lying, though small corrugations and some faults are known. For most of its length both edges are turned up and the depression is known as the Akitio Syncline.

Another hilly strip of folded older rocks lies to the east, backing the coast for many miles. It is similar in structure and content to that along the west side of the Akitio Syncline. It averages six miles across and stretches from Flat Point, twenty-five miles south-east from Masterton, for a hundred miles. Farther north—that is, from a point east from Waipukurau—the hills are lower and the belt narrows as the sea encroaches. Probably here, as at the north end of the hills to the west, the structures are more gentle.

Some change in structure is manifest in East Wellington south of the Eketahuna-Alfredton-Tinui line. The oblique faulting near Eketahuna has already been noted. Though the coast hills continue at least another twenty-five miles south from Tinui, the place of the Akitio Syncline adjoining on the west is taken by two large earth-blocks relatively elevated, tilted west, and consisting chiefly of greywacke, veneered with young Tertiary. The upland strip west of the Akitio Syncline also changes. Near Alfredton the Puketoi Range, with crests well over 2,000 ft. above sea-level, lessens in height and near Masterton, twenty miles to the south, the block disappears under the gravels of the Wairarapa lowlands, a depression forty-five miles long and ten to twelve miles wide. Greywacke mountains lie east and west and gravels from them cover most of the low country.

Oil Possibilities.

North of Hawke Bay there are four or five puckers near the trough of the Wairoa Syncline. In the low country near the sea these structures are poorly exposed, but farther north the outcrops show gentle anticlines with good closure. The young Tertiary beds of this region, however, are very thick (15,000 ft. to 25,000 ft.). As they are decidedly arenaceous they are unlikely sources of oil, and any possible pool in the old Tertiary or late Cretaceous is quite beyond the reach of the drill.

The Mangapahi (Mangaone) and Morere anticlines east of the Wairoa Syncline are large structures each covering about a hundred square miles. They carry structurally high areas and are not extensively faulted. The well-known Morere gas spring is on the west flank of the Morere Anticline, and in the Kopuawhare valley, on the east flank, combustible gas escapes at several points along a fault and oil-saturated greensand of early Tertiary age outcrops. The late Tertiary strata are eroded from the broad tops of both structures and the thickness of the remaining cover of middle Tertiary beds is of the order of 3,000 ft.

There is a gentle irregular anticline on the warped block forming Mahia Peninsula. A fault exposes early Tertiary beds in two localities along the east coast, and oil-smelling greensand outcrops at one point. The covering rocks belong to the late Tertiary and are many thousands of feet thick.

The west limb of the Wairoa Syncline extends south on the west side of Hawke Bay. The dips decrease from about 20°, where the beds overlap the greywackes of the highlands, to perhaps 3° along the coast, twenty miles to the east. This great monocline is well exposed for fifty miles, but south of the Ngaruroro River is concealed beneath terrace gravels. The beds all belong to the late Tertiary, and their thickness steadily decreases from about 25,000 ft. at the north end to perhaps 4,000 ft. at the south. They consist chiefly of conglomerate, sandstone, silt stone, and shelly limestone—unlikely sources of oil; no favourable structures are known.

The gravels of the Tukituki and upper Manawatu basins in great part conceal the narrow southern portion of the Wairoa Syncline, but deep-cut streams show that only the late Tertiary beds outcrop. In places these overlap the greywackes of the highlands, but are usually in fault-contact with them. Greywacke veneered with young Tertiary outcrops at several points along the east edge of the depression and in the hill country immediately to the east, so that it appears unlikely that strata older than the middle Tertiary are anywhere present; even if favourable structures were known the chances of petroleum occurring in commercial amount are small.

There are many outcrops of early Tertiary and late Cretaceous rocks along the Raukawa-Whangai-Puketoi hill-belt, and gas-springs and rocks that smell of oil occur. Though at least one deeply eroded anticline is known, and though there is evidence that the numerous fault-blocks have in places a crude anticlinal arrangement, nevertheless shears and fractures are so numerous, the structure in general so complex, and the patches of Tertiary cover so scant that oil accumulations probably do not occur. Similar remarks apply to the coastal hill ranges. In both the structures become less intense and the Tertiary cover more extensive toward the north.

The Akitio Syncline between these hill ranges has more favourable features. There is an extensive floor of argillaceous middle Tertiary rocks, and the dark shales that smell of oil and the porous beds of the unconformably underlying late Tertiary and early Cretaceous outcrop in the hills on both sides. The small anticlines that pucker the floor of the depression mav repay investigation.

In the south-east corner of Wellington inflammable gas escapes at Blairlogie, eighteen miles east of Masterton, and the black shale, the probable source rock for the oil occurrence of the East Coast region, extends into the district. Greywacke occupies much of the area, and where younger rocks occur their thickness is not great and their structure so strong that oil accumulations are unlikely. The low country is gravel-covered and no oil-seepages or gas-emanation are known.

For further details of the geology of the Hawke's Bay-East Wellington district see McKay (1887, B) Ongley (1930 and 1935), Henderson (1933), and Quennell and Brown (1937).

MARLBOROUGH AND NORTH CANTERBURY.

In the South Island, south-east Marlborough and North Canterbury, on the east side of the New Zealand north-east-striking mountain axis, continue the geological conditions existing in East Wellington. The structure and sequence of the late Cretaceous and Tertiary rocks are similar, and indications of oil are known at several points. The deforming earth-stresses seem to have been more severe; the Kaikoura Ranges are thousands of feet higher than the Tararua Mountains, and, in the low country, the deformations of the younger rocks are stronger and the basal greywacke is exposed over larger areas. Altogether the chances of commercial oil are very poor and "there is a complete absence of most of the structural conditions essential for a productive field" (Fyfe and Healy, 1935).

For general accounts of the geology of the Marlborough and North Canterbury districts see McKay (1890), Thomson (1920), and Fyfe and Healy (1935).

ROTORUA–TAUPO DISTRICT.

The Rotorua–Taupo district occupies the roughly triangular area down-faulted between the greywacke highlands of the Urewera country and the volcanic plateau that continues the Hauraki Peninsula southward. Farther south the Kaimanawa Mountains on the east oppose the Hauhungaroa-Rangitoto highlands on the west; both are of greywacke. Carburetted hydrogen is given off in small amount by many of the hot springs, and at Waiotapu one group of hot pools yields a little petroleum (Morgan, 1922). This may originate from (1) the reaction of volcanic gases, (2) the distillation of vegetable material entombed in the tuffs, or (3) the escape of petroleum from underlying sedimentary strata. Only the third hypothesis offers any prospect of commercial production, but there is no evidence supporting it, and most geologists prefer the second hypothesis.

For an account of the geology of the Rotorua–Taupo district see Grange (1937).

NORTH AUCKLAND.

A little combustible gas that smells of petroleum is known to occur in North Auckland, and oil-seepages have been reported. The gas escapes from bores for water in thick dark mudstones of late Cretaceous or early Tertiary age. These rocks, which occupy a considerable area in North Auckland, were deformed during the early Tertiary mountain-building movements and have a decidedly complex structure. In the middle Tertiary a thick sheet of arenaceous sediments covered their eroded surface and the crust was again warped, tilted, and differentially elevated during the late Tertiary orogeny. The earth-stresses of the different periods were also in part relieved by the intrusion of molten rock, and volcanoes ejected basaltic material up till Recent times. Though large patches of the Middle Tertiary sheet are still uneroded, especially in the southern part of North Auckland, and the presence of suitable structures has not been disproved, the general conditions seem to be unfavourable for the occurrence of oil in commercial amount.

South of the Waitemata the North Auckland earth-fold is represented by the ranges of the King-country. A broad synclinal down-warp, drained north by the Waipa and south by the Mokau, lies between the upland belt along the west coast and the Rangitoto-Hauhungaroa ranges west of Taupo. Cretaceous and early Tertiary beds are not known. Only patches of the Tertiary sheet remain on the uplands, and even in the down-warp the cover is thin and inliers of Mesozoic rocks appear on its floor as far south as Aria. This depression merges southward into the Taranaki lowland.

For details of the geology of the north and south-west parts of Auckland see Ferrar (1925 and 1934), Henderson and Grange (1926), Williamson (1932), Henderson and Ongley (1923).

TARANAKI DISTRICT.

Structure.

The Taranaki district occupies a portion of that part of the New Zealand area between the North Auckland and Nelson folds. It lies south of an east-west line joining Mokau and Taupo and west of the mountain axis. The sea readily attacks the weak young beds of this large basin of deposition and, were it not for the vast buttress of Mount Egmont, would probably have encroached over several thousands of square miles of the existing land.

The Oligocene beds on the floor of the Waipa-Mokau depression, chiefly coal-measures and mudstone overlain by a thick limestone, are southward covered with the middle Tertiary strata of the Taranaki region. These consist of a great sequence of mudstones, silty argillaceous sandstones, sandstones containing lenses of shelly conglomerate and pebbly sandstone, and having a set of coal-measures near their base. The strata have a general low dip to the south-west, in which direction younger and younger groups of beds crop out to the Wanganui coast. All are of shallow-water origin, and the Tertiary sequence in this part has a thickness of the order of 14,000 ft. Several erosion intervals have been recognized, but in general the beds of the overlying group conform in strike and dip with those below; and this, together with the uniformity in texture and composition, makes the breaks difficult to follow inland from the excellent exposures along the cliffed coast.

Though the strata of the great Taranaki monocline dip in general at low angles to the south and west, several strong faults and belts of irregular gentle folding are known. The coastal uplands of south-west Auckland narrow to the upthrust block that forms the Herangi Range. This decreases in height southward where Tertiary sediments overlap, and a very gentle faulted anticlinal continues the structure south for a few miles. Some twenty-five miles south-south-west a low-dipping anticline south of Okoke may in some way be connected with the same uplift. The strong fault-zone along the west edge of the Waipa-Mokau depression continues south far into the Taranaki district, where it grades into a gentle anticline, which may extend from Whangamomona south-west nearly to Strathmore. About a dozen miles east of New Plymouth an east-west zone of low, irregular dips extends from the volcanic cover ejected by Egmont to the Waitara River, and in the south what looks like a very gentle anticline is exposed along the cliffs near Patea.

It must be noted that the dips of the Pliocene and late Miocene beds of Taranaki are, in general, so small that care is necessary to eliminate the possibility of mistaking local current or irregular bedding—which in places near conglomerates is quite obvious—for dips due to warping and folding.

The debris Mount Egmont and its neighbours have ejected covers 1,000 square miles of Taranaki. Geologists have examined in detail another 1,500 square miles, but an area of 6,000 square miles to the south-east, consisting of flat and gently dipping Tertiary strata, has had little attention. No oil-seepages or gas-escapes, however, are known in the last-mentioned territory.

Oil Possibilities.

Except for the volcanic vents that supplied Egmont and the other ranges, sedimentary rocks outcrop on the surface or underlie the whole of the Taranaki region. The aggregate of the measured maximum thicknesses of the different Tertiary series is about 14,000 ft. and, except along the north, where the younger groups are eroded, and along the east margin, where the younger series overlap on the greywackes, probably at least 8,000 ft. of Tertiary sediments are elsewhere present. The strata are predominantly of shallow water marine deposition, though tuff occurs at several horizons as well as two sets of coal-measures and some terrestrial beds toward the base of the sequence. Much argillaceous matter occurs which entombs large amounts of animal remains, and, especially in the deeper beds, a great deal of fragmental vegetal material. There is, in fact, an abundant source of oil and, as the rocks are not metamorphosed, the whole group is potentially oil-bearing. At New Plymouth oil is produced in semi-commercial amount; in the last few years the output has been over a million gallons and in all close on three million gallons.

Strong escapes of oil take place from time to time on the foreshore at New Plymouth breakwater close to a mass of coarse-textured andesitic rock which in some way is considered to be connected with the seepage. The cover of volcanic debris conceals the relations of this mass to the Tertiary strata; it is interpreted either as a vast plug or series of plugs intrusive into them or as a volcanic neck round which they were deposited. Gravimetric observations seem to indicate that the volcanic islands of the Sugar Loaves together with Paritutu, a pike on the shore 505 ft. high, belong to a single large body of rock which in depth greatly decreases in size; in fact, that the outcrops of volcanic rock are the ruins of a volcano of which the vent pierces the Pliocene strata. Owing to their uniformity and the absence of good key beds the numerous oil-wells at New Plymouth do not afford positive proof of the structure of the underlying sediments. The data suggest that the rocks maintain the low regional dip to the south-west of other parts of Taranaki and that the volcanic masses do not noticeably affect their structure. The bulk of the oil has come from a depth between 2,100 ft. and 2,300 ft. below sea-level, but there are oil-bearing horizons at about 1,000 ft. and 3,000 ft., and "shows" of oil and gas were got nearly to the greatest depth attained (5,726 ft.). The oil horizons are indefinite. At the most promising, neighbouring wells yielded oil at somewhat different depths in very different amounts; probably the horizon is made up of sandy lenses separated by clays. To account for their higher output some have suggested that the better wells penetrate oil sands connected by fracture, in part perhaps along a dyke contact, with a deeper source; but since no well has yet yielded a million gallons even a sand lens only 2 ft. or 3 ft. thick seems competent to give this amount. The oil contains an unusually high quantity of the benzenoid and cyclo-paraffin constituents which may owe their origin to the effects of volcanic

heat on oil already existing in the sediments (Easterfield and McClelland, 1923). Others have speculated that the oil is derived from the distillation of deep-lying coal-beds.

The known oil is found south-east of the great igneous mass of which Paritutu and the Sugar Loaves are the remnants. The petroleum seepages are on the up-slope side of the contact of the igneous rock with the strata of the Taranaki sedimentary monocline and may be escaping from a trap structure on the seaward side of the Sugar Loaves. The overflow from the oil-pool in the hypothetical trap structure fed, and perhaps is still feeding, the oil-sand the wells at New Plymouth tap. On this interpretation a well on the shore west of Paritutu drilled through its projecting base of igneous rock into the sediments below might give good results.

The emanations of combustible gas, some smelling of kerosene, are distributed along a belt several miles wide that extends for thirty miles east-south-east from New Plymouth to Strathmore. This direction is, roughly, parallel with the strike of the upper Miocene beds of the district. The gas escapes from vents in upper Miocene and lower Pliocene strata as well as in the cover of volcanic fragmental material. The general strike of the Pliocene beds is a little south of east, and that of the Miocene beds about east-south-east. The most promising oil-horizon at New Plymouth is close to the middle of the highest group (Urenui Series) of the upper Miocene beds, and the evidence of the distribution of the gas suggests that it is derived from the same series.

North of the belt of gas-escapes no oil-seepages or emanations of gas are known. The lower part of the Tertiary sequence of Taranaki is exposed in this area and contains many thousands of feet of strata with all the fundamental conditions necessary for the occurrence of petroleum in commercial amount. Indeed, the deep bores at New Plymouth, Tarata, and Huiroa encountered gas and a little oil at many points in this lower group of beds. Few bores, however, have reached this part of the sequence and none has penetrated to the horizons represented on the outcrop part of the basin of deposition by coal-measures. Down the dip these and other terrestrial beds will probably grade into the shallow water and off-shore deposits that most oil geologists look upon with favour.

The dips over the greater part of Taranaki are low. In the explored area, except near the few strong fractures close to the north border, the dips are rarely more than 10° or 12°, and away from the faults in the northern half may average 5° or 6°; in the southern half the average may be 3°, and there are many outcrops where the beds are flat or the dip undeterminable. Migration of oil along such gently inclined strata is slow, especially as most of the sandy layers are more or less clogged with clay. Oil may thus accumulate where the upside dip flattens to a "structural terrace," or where the pitching axis of a low anticline on the regional slope flattens and forms a "nose." Such structures are probably more numerous than well-shaped definite anticlines and domes and some of them should be drilled.

The slow migration of oil along flatly dipping strata increases the importance of the size, attitude, and distribution of reservoir beds relatively to that of structure. Sand-lenses form generally in shallow water and are preserved when other beds cover them during the down-swing of a crustal oscillation even if small and marked in the sequence only by an inconsiderable disconformity. The oil at New Plymouth may saturate a series of sand lenses in the middle of the Urenui beds, perhaps at a break in

deposition so far unrecognized in the exposures of this group of strata along the coast to the north-east. Certainly in Taranaki the possibility of oil having accumulated above breaks in the sequence seems worth considering.

Details of the geology of the Taranaki district and of most of the wells bored are contained in reports by Park (1887), Clarke (1912), Morgan (1914 and 1927), and Grange (1927).

MURCHISON DISTRICT.

The highlands of western Nelson are part of an intensely compressed belt in which large blocks of the brittle crust have been uplifted, warped, and tilted into mountain ranges that are separated by elongated fault-angles and other complex depressions. Tertiary strata floor the Aorere, Takaka, and Nelson depressions, but the marine sediments are too thin to be likely to yield oil in commercial amount and no indications suggest its presence in them. The Murchison intermontane depression and the Inangahua-Grey graben, which opens widely to the south, both contain strong oil-seepages and emanations of combustible gas.

The Murchison depression is a graben extending north and south for fifty miles, averaging about eight miles across, and entirely surrounded by mountains. Folded and faulted Tertiary beds occupy the area and the highlands on either side consist of igneous and metamorphosed rocks from which a Tertiary sheet that formerly extended over the area has been mostly stripped. The strata in the depression belong to the middle and early Tertiary; possibly some are of late Cretaceous age. They consist chiefly of mudstones, sandstones, limestones, and their intergradations, the argillaceous members being everywhere prominent. There are also two sets of coal-measures, one at the bottom and the other near the top of the sequence, together with conglomerates and other terrestrial beds.

The folds in the beds are along the length of the depression and are decidedly strong, the dips averaging perhaps 60° and wide zones being nearly vertical. There are three rather ill-defined and broken anticlinal structures and two more definite and easily traced synclines. The axes of the anticlines are sharp and marked by vertical dips and shears along which decided movement has brought the underlying old rocks in places to the surface. The main anticlinals along the Blackwater and Matiri valleys are traceable for many miles.

Thick mudstone, black with carbonaceous material, occurs low in the sequence and, together with other argillaceous beds rich in animal and plant remains, constitutes a sufficient source for oil. In the Warwick valley near the edge of the depression oil seeps out at several points in faulted beds belonging to the youngest strata. Other seepages and gas-escapes occur along the axes of the Blackwater and Matiri anticlinals. One unsuccessful well has been sunk on the Blackwater Anticline. With such sharp structures chance enters largely into the business of prospecting.

For general accounts of the northern part of West Nelson and the Murchison district see Fyfe (1930) and Henderson (1937).

KOTUKU DISTRICT.

Structure.

The well-known seepage at Kotuku, about fifteen miles south-east from Greymouth, is near where the widely flaring Inangahua-Grey graben merges into the lowlands of North Westland. The region is structurally analogous

with West Auckland and Taranaki. A broad graben opens southward into a coastal lowland floored with flat-lying Tertiary strata; but in Westland no great volcano protects these young weak beds from wave-attack, and only a remnant of a few hundred square miles survives, in great part covered with detritus from the Alps and extending as a narrow strip north from Ross.

The Davy Range, a block tilted to the west, forms the south end of the Paparoa Mountains, the highlands on the west side of the Inangahua-Grey graben. The ancient greywackes of this tilted block lie in the core of the Brunner Anticline, a major structure, ten miles across its open northern end. It pitches south, in which direction it extends at least fifteen miles. Thick Oligocene limestone, outward-dipping from the axis, curves round the south end in a prominent ridge. Farther south, gravels and moraine almost entirely conceal the Tertiaries and it is not known if other structures occur along the same line of folding.

The northern narrow part of the Inangahua-Grey graben is essentially synclinal in structure, the Tertiary beds along its margins dipping toward the trough. Old and middle Tertiary strata showing decided dips are well exposed in the northern end of the area and, in the basin of Rough Stream some miles east of the Landing, reversals of dip suggest the presence of an anticline. For the next thirty miles young fluviatile deposits and late Tertiary gravels and sandstones occupy the depression. South of Nelson Creek the Pliocene beds show evidence, by no means conclusive, of a gentle north-south anticlinal fold. Possibly this fold is connected with the Kotuku seepage which, on rather slender evidence of two or three outcrops and from bore logs, has been interpreted as occurring on a low irregular anticline. This seepage, which is much the most prolific in New Zealand, saturates with oil several acres of the gravels and moraine that here mask the Tertiary beds. Recent geophysical work suggests that the oil reaches the surface on the upthrow side of a fault or sharp warp that strikes north-west and depresses the country on its south-west side about 200 ft.

Compressive forces upthrust the earth-blocks that make up the Paparoa Mountains and the Brunner Anticline. The same stresses transmitted through the basal complex under the young beds of the graben and the coastal lowlands and perhaps renewed along the same lines of weakness may well have raised other folds in the Tertiary strata of its floor in addition to the anticlines known in the Inangahua basin and the Kotuku district.

Oil Possibilities.

The thick dark calcareous Kaiata mudstone (2,000 ft. to 3,000 ft.) overlying the 4,000 ft. or more of late Cretaceous and early Tertiary coal-measures is a much more likely source of petroleum than the latter, which consist of terrestrial beds. Still higher in the sequence are middle Tertiary coal-measures, mudstones, sandstones, and limestones, and late Tertiary mudstones, sandstones, and conglomerates—in all close on 3,000 ft. thick. The limestone has been considered as a storage bed and as itself a possible source of oil, for at several localities the rock when freshly broken yields an evanescent smell of oil.

At Kotuku four bores at least, and probably six, have penetrated the altered old rocks below the Tertiary cover. Late Cretaceous and early Tertiary beds are absent, and if the oil is derived from these beds and is migrating along the contact with the old rocks one would expect petroleum

in the jointed limestone and the porous underlying deposits. These, however, contain but a trace of oil, and much the greatest quantity is found within 150 ft. of the surface, hundreds of feet above the limestone horizon which at the seepage is about 500 ft. in depth. On this evidence the oil is derived from Pliocene mudstone and carbonaceous shale. In this region the older Tertiary strata have nowhere been tested by a bore in a structure that is suitable for the accumulation of petroleum. Such favourable structures may well exist in the large areas of the graben covered with gravel and moraine.

For details of the geology of the southern part of West Nelson and North Westland and of the Kotuku Oilfield see Morgan (1908 and 1911) and Henderson (1917 and 1934).

OIL NEAR MARTIN BAY.

Small isolated areas of Tertiary rocks are known in South Westland and form the headlands north of Big and Martin bays in north-west Otago. Tertiary strata probably underly much of the lowlands of Westland and may extend under the sea-floor for some distance to the west. Park (1921, p. 15) postulates a fault along the west shore of Fiordland, and to this the straightness and height of the rock-bound coast, the absence of outlying reefs, and the depth of water off-shore lend support. At several points between Martin Bay and Milford Sound oil is reported to seep out on or near the shore. The schists and igneous masses of the highlands of Fiordland are most unlikely sources for this oil, which possibly is derived from submerged Tertiary beds and finds its way to the surface along a fault-zone.

SOUTHLAND DISTRICT.

In the Southland district Tertiary and Recent deposits floor a structural depression that extends along the Waiau Valley from Foveaux Strait to the head of Lake Te Anau, a distance of about eighty-five miles. To the west lie the mountains of Fiordland and to the east a line of elevation marked by the Livingstone, Takitimo, and Longwood ranges. The Southland Plain extends for forty miles east from the Takitimo and Longwood highlands to the broken hilly country beyond Mataura River ; the lower slopes of the Taringatura and Hokonui hills, twenty-five miles from the sea, border these lowlands on the north.

The Waiau River drains the large structural depression which the Takitimo mountain-mass, projecting west ten miles beyond the front of the adjoining highlands, divides into two parts connected by a relatively low strip eight miles long and six miles wide. The southern portion, eighteen miles by twenty-four miles, is essentially a wide fault-bounded syncline open to the south and closed along the north-east. Park (1921, p. 66, and map, p. 28) notes the presence of an anticlinal structure in the Clifden–Orawia area close to the east side of the depression. The dips are not high, 15° to 20°, and the wide fold strikes south-west. The strata are sandstone, mudstone, limestone, and their intergradations, the beds being of Oligocene and Miocene age. Altogether about 2,400 ft. of strata are exposed in this neighbourhood, but the underlying rocks do not outcrop and in other parts of the Waiau depression the Tertiary sequence is decidedly thicker.

Park (1921, p. 53) shows the northern part of the Waiau depression, forty miles long and averaging twelve miles across, as a wide faulted syncline of Tertiary sandstones, grits, and conglomerates. There seem, however, to

be many irregularities of structure. In the constricted central part of the depression a large amount of more or less calcareous mudstone in massive bands and in thinner layers alternating with argillaceous sandstone is present, as well as grits and conglomerates, the whole being over 4,000 ft. thick (p. 50).

In the northern part of the depression coarse-textured rocks predominate in the Tertiary; in the narrow central part dips are high; and, in both, favourable structures are not known. Conditions seem more favourable in the southern portion, but so far no oil seepages, gas emanations, or other positive indications of the presence of petroleum have been proved to occur.

Tertiary rocks outcrop on the west margin of the Southland Plain at the base of the Longwood Range and at Nightcaps farther north. At Centre Bush fifteen miles to the east, near the Hokonui hills and close to the north edge of the lowlands, there is a broken range of low hills formed of middle Tertiary limestone. That middle and early Tertiary beds underlie much of the plain seems probable. "The regional structure of the Southland plains, from the Hokonui hills on the north-east to Nightcaps and Otautau on the west, suggests a broad synclinal depression, flanked on the east and west by Mesozoic and older rocks. This synclinal depression is ten to fifteen miles wide in its northern part, but becomes broader southward and appears to plunge in this direction. Over much of this region the structure of the underlying beds is obscured by alluvium, and it is only round the edge of the region that the coal-measures and marine beds outcrop. Far out in the plain these beds possibly are gently folded into closed domes and anticlines which may contain commercial accumulations of gas and oil, but these structures will be difficult to find by ordinary field methods owing to the alluvium" (Macpherson, 1937, pp. 196–97). It should be noted that the limestone hills at Centre Bush are residual along or near the trough of a north-south syncline (p. 197).

MOERAKI DISTRICT.

Sands smelling of petroleum occur in the beach at Moeraki about forty miles north from Dunedin. Late Cretaceous and old Tertiary beds resting on the schists of Otago form a strip three to four miles wide extending along the east coast for about fourteen miles north from Shag Point. Somewhat younger rocks, probably deposited after a period of erosion, and ranging in age up to the Miocene, continue the coastal strip north and south. About 2,000 ft. of late Cretaceous and old Tertiary rocks are present. The lower beds, making up about two-thirds of this thickness, are conglomerates and coal-measures, coarse-textured rocks of terrestrial origin; about 600 ft. of dark carbonaceous shales, greensands, and grey sandstones overlie. These latter are the possible petroliferous beds. The whole group of sediments dip seaward, and this, combined with the thinness of the oil rocks, makes the chance of a commercial accumulation very small. These oil-bearing rocks, however, may extend north under the considerable areas of middle Tertiary beds of North-east Otago and South Canterbury. In these an anticlinal structure occurs in the Oamaru district just to the north.

Still farther north the gravels of the Canterbury Plain cover 3,000 square miles of lowland, parts of which Tertiary strata certainly underlie. All that can be said of this region is that the presence of oil has not been definitely disproved.

For details of the geology of the Moeraki and Oamaru districts see McKay (1887A) and Park (1918).

SUMMARY OF GEOLOGICAL OCCURRENCES.

There are at least two considerable oil-forming periods in New Zealand. The younger occurred in early Pliocene and late Miocene times and the older in the early Tertiary and late Cretaceous. To the former belong the oil-yielding rocks of New Plymouth and Kotuku, and to the latter those of the East Cape - Gisborne district, Hawke's Bay, and East Wellington, Marlborough and North Canterbury, and Moeraki. The middle Tertiary limestones also contain a trace of oil at many points, though no seepages can be attributed to them. There is some evidence that the thick mudstones of slightly younger age are in places petroliferous. These dark argillaceous beds in the Gisborne and Hawke's Bay regions smell of oil at many points and they may well be the source of the oil in the Murchison basin, though here black carbonaceous shales of early Tertiary age also occur.

In the petroliferous districts there are numerous examples of the kinds of structure that in other parts of the world contain oil-pools. In the flat-lying beds of Taranaki structural terraces and noses in addition to gentle anticlines and domes have been described. Here also monoclines sealed by unconformities, faults, or igneous intrusions may occur as well as isolated sand lenses at unconformities or elsewhere in the Tertiary sequence. Similar structures, together with anticlines formed by the settling and compaction of strata over buried hills, are possible in North Westland and the Grey-Inangahua graben. In the latter sharp-fractured folds are to be expected, such as are present in the Murchison basin. There is a wide range of structures in the East Coast districts. In the Wairoa and Akitio synclines the simple surface structures may become more pronounced below each set of beds. In the Gisborne district similar folds are likely and the crude arrangement of faulted Tertiary blocks in disordered anticlinals or synclinals may well overlie intensely plicated anticlinoria and synclinoria in the Cretaceous rocks beneath.

GEOPHYSICAL PROSPECTING.

A few years ago the geologist had to rely on what he could see on the surface, supplemented with what information he could get from bores; to-day he has many geophysical instruments to assist him. Geophysical instruments measure or record physical phenomena depending directly on the physical properties of the rocks below the surface. The magnetometer records differences in the earth's magnetic field. The seismograph measures the velocity of propagation of elastic waves through the different formations. The ratiometer and other electrical appliances gauge the relative electrical conductivities of rocks and of the fractures in them. The torsion balance directly evaluates the rate of change of the intensity of gravity. None of them positively determines the presence or absence of a valuable deposit or of a particular structure. The geologist interprets the data of the geophysicist, combines them with facts observed in the locality and with his knowledge of the rocks and structure of the region, and then draws conclusions that only the driller can test. The immediate and impressive success of geophysical prospecting for oil in Texas and Louisiana demonstrated the value of the methods. In that region they have markedly reduced the hazard risk of development and have given to prospecting campaigns that in former years only the most reckless "wild catter" would have seriously considered a fair hope of success. On the other hand, in some areas long-continued and costly geophysical work has yielded nothing that

careful surface observation and logical deductions had not already ascertained. Many geological problems, however, on account of the imperfect data, are susceptible of more than one interpretation, and geophysical methods may add the little more required to convert doubt to reasonable probability ; but until the geophysical work is actually carried out one may not be able positively to state that it will add anything to visual observation.

In New Zealand there are some oil problems to which geophysical methods are obviously applicable. Volcanic debris thickly covers a large part of Taranaki, which part includes the petroleum seepages and the semi-commercial wells of New Plymouth as well as most of the belt yielding emanations of combustible gas. The nature and attitude of the subsurface rocks can be inferred with strong probability from geophysical evidence and this will enable sites to be chosen for bores that have a reasonable chance of determining whether the district is worth further prospecting or not. Without the geophysicist's aid, the task of exploring the ash-covered part of Taranaki would involve an enormously costly programme of core-drilling and would indeed be starkly futile. Similar remarks apply to North Westland, though here the area worth prospecting is smaller, the detrital cover less complete, and the history of the search for oil less encouraging. Gravels mask other probable considerable areas of Tertiary beds under the Canterbury and Southland plains, but there is no direct evidence that such rocks, if present there, do contain oil.

The geophysicist may materially help the geologist in another kind of problem. In Hawke's Bay and East Wellington the full thickness of the Tertiary and late Cretaceous beds are not everywhere present ; great sections are absent in some localities and, where the uppermost strata only are exposed it may not be possible to determine from surface evidence whether these rest on the basal greywackes or on other members of the younger group. Thus in the low sag between the Ruahine and Tararua ranges late Tertiary mudstone rests directly on, and forms a complete arch over, the greywackes that the Manawatu exposes in the gorge it has cut through the core of the structure a short distance farther south. In the same region there is no positive proof that oil-bearing late Cretaceous and early Tertiary rocks underlie the anticlinal folds of mid-Tertiary strata on the floor of the Akitio Syncline. It would be of service to the geologist if the geophysicist measured the depth to the greywacke and determined if rocks of the same elasticity as those elsewhere petroliferous existed in any of these structures.

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